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Research Article

Horizon scanning of potential new alien vascular plant species and their climatic niche space across the Arctic

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Abstract

The terrestrial Arctic faces increasing vulnerability to alien plant invasions due to climate change and intensifying human activities. Using a data-driven horizon scanning approach that leverages the Global Naturalized Alien Flora (GloNAF) database, species occurrence data from the Global Biodiversity Information Facility (GBIF), and climate data from WorldClim, we identified 2,554 potential new alien vascular plant species with climatic niches overlapping Arctic floristic provinces. Six major potential hotspots for introductions were detected, with western Alaska, southwestern and southeastern Greenland, northern Iceland, Fennoscandia, and Kanin–Pechora showing the highest numbers of potential alien species. Potential source regions for these species extended globally across diverse climate zones, with substantial contributions from proximate temperate regions in Europe and North America. Taxonomic analysis revealed that most Arctic floristic provinces exhibited compositions similar to global patterns, with only Franz Joseph Land showing significant deviation after multiple comparison corrections, although island provinces generally demonstrated greater compositional distinctiveness than mainland provinces. Zero-inflated beta regression analysis confirmed our hypothesis that species with higher absolute latitude distributions demonstrate greater potential for climatic overlap with Arctic floristic provinces. Our findings emphasize the need to develop effective biosecurity measures in high-risk regions and to proactively manage emerging invasion risks across the rapidly changing terrestrial Arctic ecosystems. This will provide a foundation for supporting community-based monitoring networks essential for early detection and rapid response initiatives.

Key words: Arctic biodiversity, bioclimatic modelling, climate change, early detection rapid response, horizon scanning, invasion science

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Introduction

The Arctic region faces escalating threats from biological invasions driven by rising human activity and climate change (Ware et al. 2012; CAFF and PAME 2017; Wasowicz et al. 2020; IPBES 2024). Unlike most areas of the world, Arctic terrestrial ecosystems have largely been shielded from the devastating effects of alien species due to natural barriers, including short growing seasons, harsh climatic conditions, and limited human activity and disturbance (Janská et al. 2010; Przybylak 2016; CAFF and PAME 2017; Wasowicz et al. 2020). However, ongoing climate change and increasing human activities are transforming Arctic ecosystems. Enhanced transport and trade networks facilitate alien species introductions, while

infrastructure development and resource extraction disturb soils, creating favorable conditions for alien plant establishment (Box et al. 2019; Wasowicz et al. 2020). This is particularly significant in Arctic environments, where soil disturbance exposes mineral surfaces and creates unconsolidated sediments that, when combined with warming conditions, support plant establishment through accelerated soil development and changes in physical, chemical, and microbial properties (Wasowicz et al. 2020; Doetterl et al. 2022). This process is intensified in and around Arctic urban areas and settlements, which function as primary introduction hubs for alien species due to concentrated trade, traffic, and horticulture (Hulme 2009; Wasowicz et al. 2020). Such human modifications and the associated propagule pressure are strongly linked to the initial establishment of alien plants; however, subsequent diffusion and invasion success are more strongly influenced by climate and habitat heterogeneity (Pfadenhauer et al. 2024). Climate change and increased human disturbance are making the Arctic increasingly suitable for a broader range of alien species (Parmesan 2006; Nievola et al. 2017; Cazzolla Gatti et al. 2019; Hansson et al. 2023; IPBES 2024; Speed et al. 2024).

A comprehensive inventory of alien plant taxa in the Arctic previously documented 341 taxa, providing a valuable foundation for understanding patterns of establishment and spread across the region. Of these, 188 had become naturalized in at least one floristic province (i.e., subdivisions of the Arctic based on floristic differences; Walker et al. 2003, 2005), and a smaller subset of 11 taxa is considered invasive, posing threats to native taxa and ecosystems (Wasowicz et al. 2020). Pathway analysis has revealed that the most common route for naturalized species is "escape from confinement," which accounts for 48% of invasive plant introductions. "Transport–stowaway" is the second most frequent pathway for invasive taxa (37%). At a finer scale, the subcategories "seed contaminant" and "transport via vehicles" have been important introduction routes, each contributing 14% of introductions. However, a significant proportion (43%) of introductions remains classified as "unknown" (Wasowicz et al. 2020). Despite regulatory efforts in regions such as Svalbard, where the intentional introduction of alien taxa is prohibited under the Svalbard Environmental Protection Act, unintentional introductions continue to pose a major biosecurity challenge. These are especially prevalent along transportation corridors and near human settlements, where propagule pressure is highest (Alsos et al. 2015). This underscores the need for improved horizon scanning, monitoring, and management strategies to mitigate the spread of alien plants to the Arctic.

Early detection and rapid response (EDRR) is recognized as a cost-effective strategy for managing alien taxa (e.g., Hitchcox 2015; Larson et al. 2020; Wasowicz et al. 2020; IPBES 2024). However, public awareness and eradication efforts often occur too late in the invasion process (Hitchcox 2015). Public awareness is crucial for bridging this gap because it can transform the public into a widespread surveillance network, creating more observers for early detection efforts (Haley et al. 2023). This "citizen science" approach is a powerful tool for EDRR, as it leverages numerous observers across large geographic areas to increase the likelihood of detecting new invasions when populations are small and localized (Larson et al. 2020). By educating and engaging citizens, managers can improve the likelihood of discovering new introductions earlier on the invasion curve, which is critical for mounting a successful and cost-effective rapid response (Hitchcox 2015; Larson et al. 2020; Haley et al. 2023). The high proportion of unknown introduction pathways, coupled with the need for early intervention, underscores two critical

knowledge gaps: identifying potential new alien taxa likely to find niches in the Arctic and understanding their likely introduction pathways. Addressing these gaps is essential for developing effective pre- and early post-border preventive management strategies (Sandvik et al. 2022; IPBES 2024).

Horizon scanning is a systematic process for identifying future threats and opportunities to inform proactive management (Roy et al. 2014; Seymour et al. 2020). For biological invasions, the goal is to identify potential new alien taxa that are not yet established in a region but could arrive, establish, and negatively impact native biodiversity. This is achieved by assessing three key stages: the likelihood of arrival, the probability of establishment, and the potential for negative impacts (Roy et al. 2014; Kendig et al. 2022). Often, this has been accomplished through expert consensus approaches that rely on labor-intensive literature searches and workshops to collaboratively compile and rank taxa lists (Roy et al. 2014; Hughes et al. 2020; Dawson et al. 2022; Norwegian Biodiversity Information Centre 2024). While invaluable, this process can be limited by the availability of interdisciplinary expert knowledge, particularly taxonomic expertise, which can create a bottleneck. More recently, data-driven methods have emerged as a powerful preparatory step. These methods use statistical tools to systematically screen large global datasets of potential invaders, often numbering in the thousands, to create a manageable, prioritized list for subsequent expert assessment (Evans and Drake 2022; Kendig et al. 2022; Ivison et al. 2025). Integrating a data-driven approach with expert evaluation offers significant potential to enhance the efficiency and effectiveness of horizon scanning by focusing expert time on the most likely threats.

Here we employ a data-driven horizon scanning approach to identify potential new alien vascular plants across the terrestrial Arctic. Although Arctic plant habitats form a diverse and complex mosaic, regional east–west patterns of vascular plant species richness reflect differences in glaciation history, geology, and geography (i.e., floristic provinces; Walker et al. 2005). This necessitates regional-scale analyses to guide local management strategies while preserving a circumpolar view of invasion risks. We use the list of alien vascular plants known to be naturalized in some part of the world as a pool of potential new aliens to the Arctic (Global Naturalized Alien Flora database, GloNAF; van Kleunen et al. 2019). Our objectives are to (1) identify which of these taxa have the potential to establish in the Arctic based on estimates of overlap in current climatic niches; (2) determine which Arctic floristic provinces may be most susceptible to new alien plant establishments; (3) identify regions that may serve as important sources of future alien plant introductions to the Arctic; and (4) assess whether species' existing latitudinal distributions influence their potential for climatic overlap with the Arctic. We hypothesize that species currently distributed at higher absolute latitudes (i.e., both boreal and austral) will show greater climatic overlap with Arctic regions.

Methods

Study area

We used the delimitation of the terrestrial Arctic provided by the Circumpolar Arctic Vegetation Map (CAVM; Walker et al. 2003). The CAVM originally included 29 floristic provinces, but for the purpose of this study we used a restructured list of 23 provinces following other relevant research (Daniëls et al. 2013;

Wasowicz et al. 2020) and the Pan-Arctic Flora (PAF) delimitation (Nordal and Razzhivin 1999). Specifically, the North Beringian Islands and northern Alaska were merged into North Alaska–Yukon Territory; West Hudsonian and Baffin–Labrador into Hudson Bay–Labrador; Northwest, Southwest, Central West, and South Greenland were merged into western Greenland; and Southeast, Central East, and Northeast Greenland were merged into eastern Greenland. North Iceland–Jan Mayen and Svalbard–Franz Joseph Land were split (Suppl. material 1: fig S1). Further, unsuitable habitats for vascular plants, such as the Greenlandic ice sheet and other glaciers, were removed (see "setup_region" in "example/R/setup/custom_setup/region/handle_region.R" on GitHub for source code).

Producing the list of potential new alien vascular plants

We used the Global Naturalized Alien Flora database (GloNAF; van Kleunen et al. 2019) as an initial list of worldwide naturalizing and alien vascular plant taxa. To focus our assessment on novel introductions and ensure taxonomic consistency, we harmonized taxonomic names and removed all plant taxa native to the Arctic ("Arctic Plant Inventory List"; Daniëls et al. 2013), along with the already confirmed alien vascular plant flora of the Arctic ("Arctic Alien Plant List"; Wasowicz et al. 2020). This produced a harmonized list of potential new alien vascular plant taxa to the Arctic for downstream analyses. Consequently, we did not assess range-expansion possibilities for already existing Arctic alien plant taxa in order to focus specifically on potential novel introductions. Additionally, we applied the precautionary principle to avoid excluding potential new alien taxa due to taxonomic uncertainty at infraspecific levels for species with many infraspecific taxa. Specifically, if the filtering process identified a species-level taxon for inclusion, we retained all associated infraspecific taxa (subspecies, varieties, and forms) in our workflow, even if some of these lower-ranking taxa had existing occurrence records within the Arctic. This approach recognizes that different infraspecific taxa within the same species may have varying invasion potential. While one infraspecific taxon might be native to, or already established in, the Arctic, others could represent invasion risks. Conversely, when the filtering process identified only specific infraspecific taxa (without their parent species being flagged; Fig. 1, step 4), we included only those particular taxa rather than expanding to the full species level. This precautionary approach ensures that our risk assessment errs on the side of inclusion.

The GloNAF list contained 13,939 vascular plant taxa known to be naturalized or alien worldwide. Both "naturalized" (has established self-sustaining populations in the wild) and "alien" (when it is not clear whether they are naturalized) taxa were included in the filtering process. The Arctic Plant Inventory List comprises 2,065 taxa, while the Arctic Alien Plant List contains 334 taxa. Both Arctic lists include taxon-specific distribution information on presence and absence in the 23 floristic provinces of the Arctic. First, the native taxa on the Arctic Plant Inventory List were sorted into "Inventory Arctic present" (including "frequent," "rare," "scattered," and "present" taxa) and "Inventory Arctic absent" (including "casual," "absent," "borderline," and "unknown" taxa; Fig. 1). The taxonomic abbreviations "aff.," "agg.," "s. lat.," "coll.," and "sp." were included in the interim name later passed to World Flora Online (WFO) for standardization. One specific row in the Arctic Plant Inventory List contained two different species: "864112 Not assigned to aggregate: *T. longicorne* (H-L, N) (R S F) / *T. perfiljevii* (D-G) (S F F)" and was

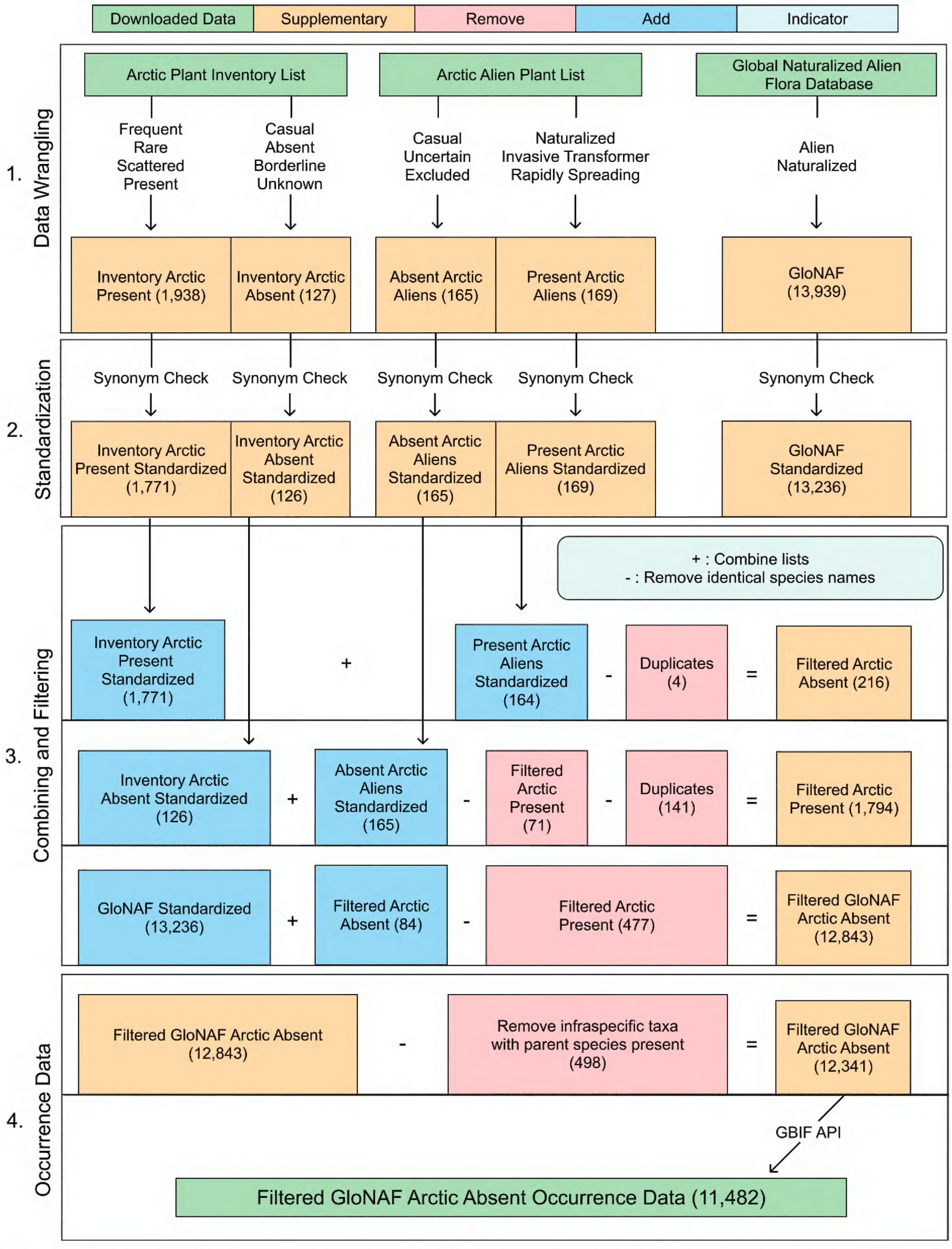

Figure 1. Workflow diagram illustrating the data processing and filtering steps to identify plant taxa from the Global Naturalized Alien Flora (GloNAF) database that are absent from the Arctic region. The process consists of four main stages: (1) data wrangling of inventory lists, including the Arctic Plant Inventory, Arctic Alien Plant List, and GloNAF database; (2) standardization through synonym checking; (3) combining and filtering of standardized lists to remove duplicates and identify present and absent taxa; and (4) occurrence data refinement through the removal of infraspecific taxa. The workflow begins with 13,939 alien naturalized taxa from GloNAF and concludes with 11,482 filtered species with occurrence records. Color coding indicates downloaded data (green), supplementary data (light orange), taxa addition steps (blue), removal steps (pink), and indicators for descriptions (light blue). Numbers in parentheses represent the count of taxa at each processing stage.

split into "*Taraxacum longicorne*" and "*T. perfiljevii*" (author names lacking) with duplicated row data. Second, the alien vascular plants on the Arctic Alien Plant List were sorted into "Absent Arctic aliens" (including "Naturalized," "Invasive Transformer," and "Invasive" taxa, termed "Rapidly spreading" in the source data) and "Present Arctic aliens" (including "casual," "uncertain," and "excluded" taxa).

We standardized scientific names for each list using the World Flora Online (WFO) package in R (Kindt 2020). We then passed the scientific names, which included varying degrees of author information, to the WFO.match function. This function checked each input taxon name against the WFO database and produced all known synonyms associated with the name as output, regardless of whether the input name itself was an accepted name or a synonym. The WFO.one function then processed these synonym sets to select a single representative name for each taxon, with accepted-status names given priority over synonyms when available (Kindt 2020). Of the initial taxa, 120 could not be automatically resolved by WFO.match and required manual handling. Each name was manually cross-referenced against multiple taxonomic authorities, primarily World Flora Online (WFO 2024) and the Global Biodiversity Information Facility (GBIF.org 2024). This manual resolution process addressed several categories of taxonomic issues, including synonymy, typographical errors, and the standardization of infraspecific ranks (e.g., subspecies, varieties, and autonyms) and taxonomic aggregates to the species level. A small number of invalid or unpublished names (27) were removed from the analysis. The specific decision, authority, and justification for each of the initial 120 manually handled names are documented in Suppl. material 1: table S3. We then used the fully standardized taxonomic names to produce the lists of taxa present or absent in the Arctic by merging and removing duplicates. Further, the "Arctic present" list was used to remove any taxa from the GloNAF list already present in the Arctic. The "Arctic absent" list was then combined with the GloNAF list, and duplicates were removed (Fig. 1).

Occurrence data

We used the name_backbone function in the R package rgbif (Chamberlain et al. 2024) to match our final filtered GloNAF list of 12,341 taxonomic names to the GBIF Backbone Taxonomy and retrieve their usage keys. In GBIF, a usage key is a unique identifier for a specific taxonomic name in the backbone. This can be an accepted name or a synonym at any rank (species, subspecies, variety, etc.). Each synonym in GBIF is linked to its accepted name via an acceptedUsageKey. When querying GBIF by the accepted usage key (also referred to as taxonKey in occurrence searches), GBIF returns all occurrence records for that accepted name and all names linked to it as synonyms in the backbone (GBIF.org 2024). This ensures that records uploaded under historical or alternative names recognized by GBIF—including infraspecific names and autonyms—are included in the download, reducing bias from excluding older synonymized records. We confirmed this behavior by spot-checking taxa with known synonyms and verifying that querying the accepted usage key retrieved occurrences for all linked synonyms.

These usage keys were then used with the occ_download function (Derived dataset GBIF.org 2025b) to retrieve records with status "present," excluding records with geospatial issues (an ensemble of 30 different issues related to coordinates, elevation, and depth; Buitrago 2020). The global records included both human

observations and preserved herbarium specimens from 1970 to 2024 with a coordinate uncertainty of less than 351 meters, to match the highest cell resolution of climate data. We chose the start year (1970) to match the temporal coverage of climate data and to maximize the number of observations and capture current taxon distributions, thereby providing climate niches that reflect contemporary taxon ranges rather than historical patterns. The download returned 51,566,131 occurrences for 11,534 different taxa.

We filtered out taxa where the logarithm of the number of occurrence records was fewer than the number of climate dimensions used to calculate hypervolume space (four; see "climate space" below). A hypervolume is a set of points within an n-dimensional space that represents the ecological niche of a taxon, where each axis corresponds to a biologically relevant variable. This framework ensures flexible modeling of complex, high-dimensional data distributions (Blonder et al. 2014). This meant taxa with < 55 occurrences were excluded to avoid inaccuracies in constructing hypervolumes, resulting in the removal of 3,034 taxa before the climate analysis. After filtering, 8,448 taxa were retained for the climatic niche overlap analysis.

Arctic climate space

Climate data were downloaded from WorldClim 2.0 (Fick and Hijmans 2017) using the R package geodata (Hijmans et al. 2023). The climate data contained 19 bioclimatic variables related to temperature and precipitation patterns, with a spatial resolution of 2.5 minutes. These data represent bioclimatic variables from 1970 to 2000 (Fick and Hijmans 2017), providing a consistent temporal baseline for cross-taxon comparisons. The climate data were mean-centered and standard-deviation scaled using the scale function in base R (R Core Team 2023) with default settings to enable meaningful comparison of climatic niche spaces across taxa.

The climate data were then cropped to the Arctic as delineated by CAVM, and the Pearson correlation coefficient ($|r_p|$) was employed as a statistical measure to evaluate pairwise linear covariations between the 19 bioclimatic variables. The absolute value of the Pearson correlation coefficient was used to quantify the strength of the correlation, irrespective of its direction. This approach allowed us to identify and select bioclimatic variables that effectively characterized the Arctic climate while ensuring these variables did not exhibit high multicollinearity ($|r_p| < 0.5$; Suppl. material 1: fig S2). Based on ecological relevance for plant growth and survival in Arctic conditions, the selected bioclimatic variables were precipitation of the warmest quarter (bio18), which influences water availability during the critical growing season; mean temperature of the warmest quarter (bio10), which constrains photosynthetic activity and reproductive development; isothermality (bio3), which reflects temperature stability important for plant adaptation; and temperature seasonality (bio4), which affects phenological responses and stress-tolerance requirements.

The taxon's climate space

Each taxon's longitude and latitude coordinates were cleaned using the coordinateCleaner (Zizka et al. 2019) package in R and an employed thinning function (see "thin_occ_data" in "R/utils/components/helpers/spatial_helpers.R" on GitHub for source code). The coordinateCleaner package was used to identify and remove occurrence

records where the coordinates were centroids of countries, in the open ocean, at the headquarters of GBIF, in urban areas, and at the location of biodiversity institutions, as well as outlier, zero, duplicate, or invalid coordinates (Zizka et al. 2019). The thinning function was used to reduce autocorrelation in the occurrence data for each taxon. We retained only one random point within a grid cell of 1 × 1 km to match the climate niche analysis raster resolution. For taxa included in the climate analysis, occurrence records were converted into spatial point data, and climate data were extracted at these points. This resulted in multiple data points for each taxon, ranging between 55 and 108,213, describing their climate niche (Suppl. material 1: fig S3).

Climatic niche space analysis

We used an adapted version of a hypervolume approach (Ivison et al. 2025) to quantify taxa's climatic niche overlaps with the Arctic climate. The Hypervolume R package (Blonder et al. 2025) operationalizes this concept and is designed to address challenges posed by large datasets, including non-normality, disjunctions, and computational intensity. In our method, we first generated taxon-specific hypervolumes using the box method, then applied the built-in project function to obtain geographical projections for each taxon's niche, using both the inclusion and probability modes.

The climatic niche space was constructed using kernel density estimation (KDE) with the hypervolume package in R (Blonder et al. 2014, 2025; Chen et al. 2024). The first step involved constructing a climatic niche model of the Arctic climate using the box method from the hypervolume package (Suppl. material 1: fig S4). The box method overlays a box (or hyperbox in multiple dimensions) around each data point or observation and estimates how dense the data are within these boxes. The size, or bandwidth, of the boxes was determined using the Silverman estimator, defined as:

$$\left(\frac{4}{n+2}\right)^{\left(\frac{1}{n+4}\right)} * m^{\left(-\frac{1}{n+4}\right)} * \mathrm{sd}(X)$$

where m is the number of occurrences, n is the dimensionality, and X is the data vector in each dimension. This corresponds to the Silverman rule of thumb for multivariate data (Blonder et al. 2025).

Next, each taxon underwent two exclusion tests to limit the time consumed by the analysis process (Suppl. material 1: fig S4). The first test used an inclusion analysis to determine whether any of the taxon's climate observation points overlapped with the Arctic climate hypervolume. Taxa were excluded from further analysis if no climate points overlapped with the Arctic hypervolume. However, if there was an overlap (>0), the taxon's own hypervolume was created and used to analyze a more precise overlap between the Arctic and the taxon's hypervolume. If the taxon's hypervolume overlapped with the Arctic hypervolume, the taxon moved on to the final part of the analysis, which was to project the taxon's hypervolume onto a raster map of the Arctic using both the inclusion and probability methods.

The same inclusion analysis method was then applied spatially to create projection maps. We used the accurate algorithm, which estimates the probability density at each test point and excludes points below a threshold of 0.5. Although this method is slower, it provides more reliable results than the fast algorithm (Blonder et al. 2025). The inclusion projection creates a binary map, where each grid cell is marked as 1

(presence) if included in the taxon hypervolume, or 0 (absence) if not. This binary map highlights potential new areas of occupancy for the taxa.

The probability analysis calculates the probability density at various points within or outside the taxon hypervolume. This is done by computing a weighted sum of the probability densities of all subsampled random points in the hypervolume, where the weights are proportional to the distance from the test point raised to the power of –1 (inverse distance weighting; Blonder et al. 2025). The probability projection generates a map with each grid cell assigned a probability density value, indicating the suitability of the Arctic climate for the taxon as a gradient rather than binary values. Higher values suggest greater suitability.

Model validation

To validate the model used in the climate niche analysis, we applied the same process to the vascular plant taxa already present in the Arctic as listed in the Arctic Plant Inventory List and Arctic Alien Plant List. This included 1,558 known Arctic taxa downloaded from GBIF using the occ_download function in the R package rgbif (Chamberlain et al. 2024; Derived dataset GBIF.org 2025a). Lastly, we identified the percentage of taxa whose climate niches were found to overlap with the Arctic climate.

Ecological analysis

We conducted several analyses to characterize potential new alien vascular plant taxa distributions and patterns. First, we quantified each taxon's potential total area of occupancy by applying the hypervolume project function from the hypervolume package in R (Blonder et al. 2025). We used the inclusion method to generate binary suitability rasters, then extracted the values to data tables and calculated the proportion of grid cells within the study region that had climatically suitable conditions based on these binary outputs. For habitat suitability analysis, we used the probability densities calculated by the hypervolume project function with the probability method from the hypervolume package, which estimates how well-suited different Arctic regions are for each taxon based on their climatic niches. To examine taxonomic patterns, we calculated the relative richness of each plant order within each floristic province as follows:

$$\text{relative order richness} = \frac{n}{N}$$

where n is the unique number of potential new alien taxa in each order in each floristic province, and N is the total number of potential new alien taxa in each floristic province. This analysis revealed how taxonomic composition varies across the Arctic. Furthermore, we analyzed the statistical significance of taxonomic compositional differences between Arctic floristic provinces and the global baseline (GloNAF) using chi-square goodness-of-fit tests. The standard asymptotic assumptions of the chi-square test are often violated in ecological data due to low expected frequencies in many categories. To address this, we employed a Monte Carlo simulation with 2,000 replicates (B = 2,000) to calculate robust p-values empirically (Hope 1968). This procedure generates a null distribution of the test statistic based on the specific structure of our data, providing results that are independent of large-sample theoretical assumptions (Good 2005). We compared the observed proportional distribution

of taxa across taxonomic orders against the expected distribution derived from the GloNAF baseline data for each floristic province. Effect sizes were quantified using Cramér's *V* for goodness-of-fit tests, calculated as:

$$\sqrt{\frac{\chi^2}{n(k-1)}}$$

where χ^2 is the chi-square statistic, n is the sample size (total number of taxa) in each floristic province, and k is the number of taxonomic orders. Effect sizes were interpreted as small ($V < 0.3$), medium ($0.3 \leq V \leq 0.5$), or large ($V > 0.5$) differences from the global baseline composition (GloNAF) (Cramér 1946). To account for multiple comparisons made across all floristic provinces, we corrected the *p*-values using the false discovery rate (FDR) method. Specifically, we applied the Benjamini–Hochberg procedure (Benjamini and Hochberg 1995) to the set of raw *p*-values from our chi-square tests. This approach controls the expected proportion of false positives among all significant results, providing greater statistical power than traditional methods such as the Bonferroni correction, which controls the more stringent family-wise error rate (Verhoeven et al. 2005). The procedure was implemented using the p.adjust function in base R (R Core Team 2023). An adjusted *p*-value (or *q*-value) below our significance level of $\alpha = 0.05$ was considered statistically significant, indicating that the taxonomic composition of that floristic province differed from the GloNAF global baseline.

To investigate the potential source regions of future alien plants in the Arctic, we first standardized the geographical representation of taxon occurrences across regions by calculating the centroid (mean latitude and longitude) of all occurrence points for each taxon within each botanical country (Level 3; Brummitt et al. 2001). This resulted in one representative coordinate point per taxon per botanical country. This step was taken to condense the output information from the hypervolume analysis while retaining the occurrence bias of each taxon's range in the respective botanical country. Consequently, a single taxon may have only one point per botanical country but multiple points across the world map.

Finally, to test whether taxa originating from higher latitudes tend to have greater climatic overlap with the Arctic, we modeled climate overlap as a function of the taxa's absolute median latitude using a zero-inflated beta regression model in R (BEZI family in GAMLSS; Rigby and Stasinopoulos 2005). We tested five models with increasing complexity to evaluate the relationship between latitude and climate overlap:

1. **Full model**—absolute latitude was used as a predictor for (1) the mean of nonzero climate overlap values, (2) the dispersion parameter controlling variance, and (3) the probability of observing zero climate overlap.
2. **Zero-only model**—absolute latitude was used as a predictor for (1) the dispersion parameter and (2) the probability of zero climate overlap, while the mean had only an intercept term.
3. **Magnitude-only model**—absolute latitude was used as a predictor for (1) the mean of nonzero climate overlap values and (2) the dispersion parameter, while the probability of zero had only an intercept term.
4. **Intercept-only model**—absolute latitude was used as a predictor only for the dispersion parameter, while both the mean and probability of zero had only intercept terms.
5. **Complete null model**—intercept terms only for all three parameters.

We compared models using the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) to determine which best explained the relationship between latitude and climate overlap patterns. AIC was used to identify models with strong predictive accuracy, while BIC—with its stronger penalty for complexity—helped ensure model parsimony. Using both criteria provided complementary perspectives on model selection (Suppl. material 1: table S1). All analyses were carried out in R (version 4.3.2; R Core Team 2023).

Results

The climatic niche overlap analysis identified 2,554 vascular plant taxa as potential new alien taxa to the Arctic (Suppl. material 2: included_taxa.csv), representing 30.2% of the 8,448 taxa that met all analysis criteria and 18.3% of the original pool of taxa (Suppl. material 2: excluded_taxa.csv). This number was derived from the list of 13,939 globally naturalizing vascular plant taxa, or 11,482 after removing taxa already present in the Arctic and downloading occurrence data. The validation procedure, applied to the 1,157 known Arctic taxa that met the analysis criteria, demonstrated a high success rate. Of these, the climate niches for 1,061 taxa (91.7%) were found to overlap with the Arctic climate. This resulted in a 59.1% success rate when considering the original pool of 1,794 known Arctic vascular plant taxa, where 401 were removed due to too little occurrence data.

The potential richness of new alien plants (i.e., the number of species with suitable climate at a given location across the Arctic) ranged from 0 to 1,273 species per km^2 cell (Fig. 2; Suppl. material 1: table S4). Based on climatic niche overlap, we identified several hotspots for potential new alien species across the Arctic. Western Alaska had the highest number of potential new alien species, with predictions peaking at 1,273 species. This number then declined to 248 species across the northern Alaska–Yukon Territory. Southern Greenland had the second and third major concentrations, with high numbers of potential new aliens in both southwestern (1,055 species) and southeastern (720 species) floristic provinces. Northern Iceland and Kanin–Pechora represented the fourth and fifth significant hotspots, with predictions reaching 622 species for both floristic provinces. Fennoscandia was identified as the sixth principal hotspot, with projections indicating the presence of 336 potential new alien species. Higher-latitude floristic provinces, such as Svalbard (45), Jan Mayen (46), Franz Joseph Land (6), and Wrangel Island (7), had fewer, but not negligible, numbers of potential new alien species.

The top five potential new alien species having the largest projected areas of climatic suitability in the Arctic are presented in Fig. 3 (left panels). *Arnica angustifolia* Vahl may find suitable climatic conditions across 95% of the Arctic region, followed by *Koeleria spicata* (L.) Barberá, Quintanar, Soreng & P.M. Peterson (94%), *Micranthes nelsoniana* (D. Don) Small (93%), *Alnus alnobetula* (Ehrh.) K. Koch (84%), and *Senecio nemorensis* L. (62%). The climatic suitability analysis (Fig. 3, right panels) indicated spatial variation in the probability of climate matching across the potential ranges. However, the highest overall suitability values were generally found in the same provinces identified as hotspots for the number of potential new alien species.

To assess whether the taxonomic composition of the potential new alien flora differed from global patterns, we compared the relative richness of plant orders in each floristic province to the GloNAF baseline (Fig. 4; Suppl. material 1: fig S5).

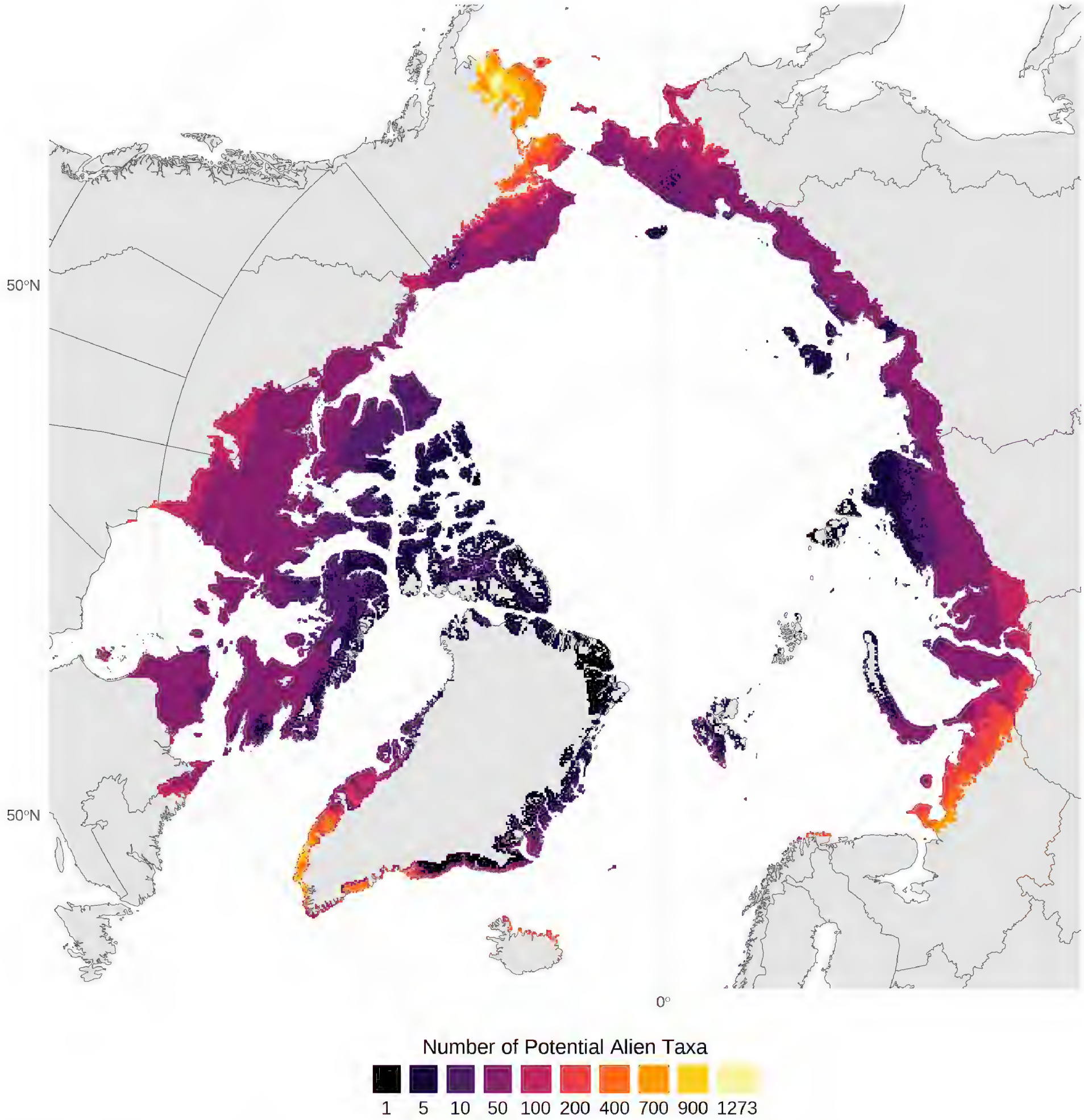

Figure 2. Hotspots of potential new alien vascular plant species richness across the Arctic, based on 1 × 1 km resolution models of GloNAF species with climatic niches overlapping Arctic regions. Darker colors represent lower numbers of potential alien species, while brighter colors represent higher numbers. The terrestrial Arctic is defined by the extent of the colored areas, delimited according to the Circumpolar Arctic Vegetation Map (CAVM; Walker et al. 2003).

The results showed that, for most Arctic floristic provinces, the taxonomic composition did not differ significantly from the global naturalized alien flora baseline. After FDR correction, only Franz Joseph Land exhibited a statistically significant deviation from the GloNAF baseline ($p = 0.0005$, $p_A d_j = 0.011$). This difference was also the largest in magnitude, with a Cramér's V effect size of 0.51, indicating a large effect, driven primarily by a pronounced overrepresentation of the order Asterales, which accounted for 33.3% of the province's potential new alien species vs. 11.8% in GloNAF. In contrast, globally prominent orders such as Fabales (9.4% GloNAF)

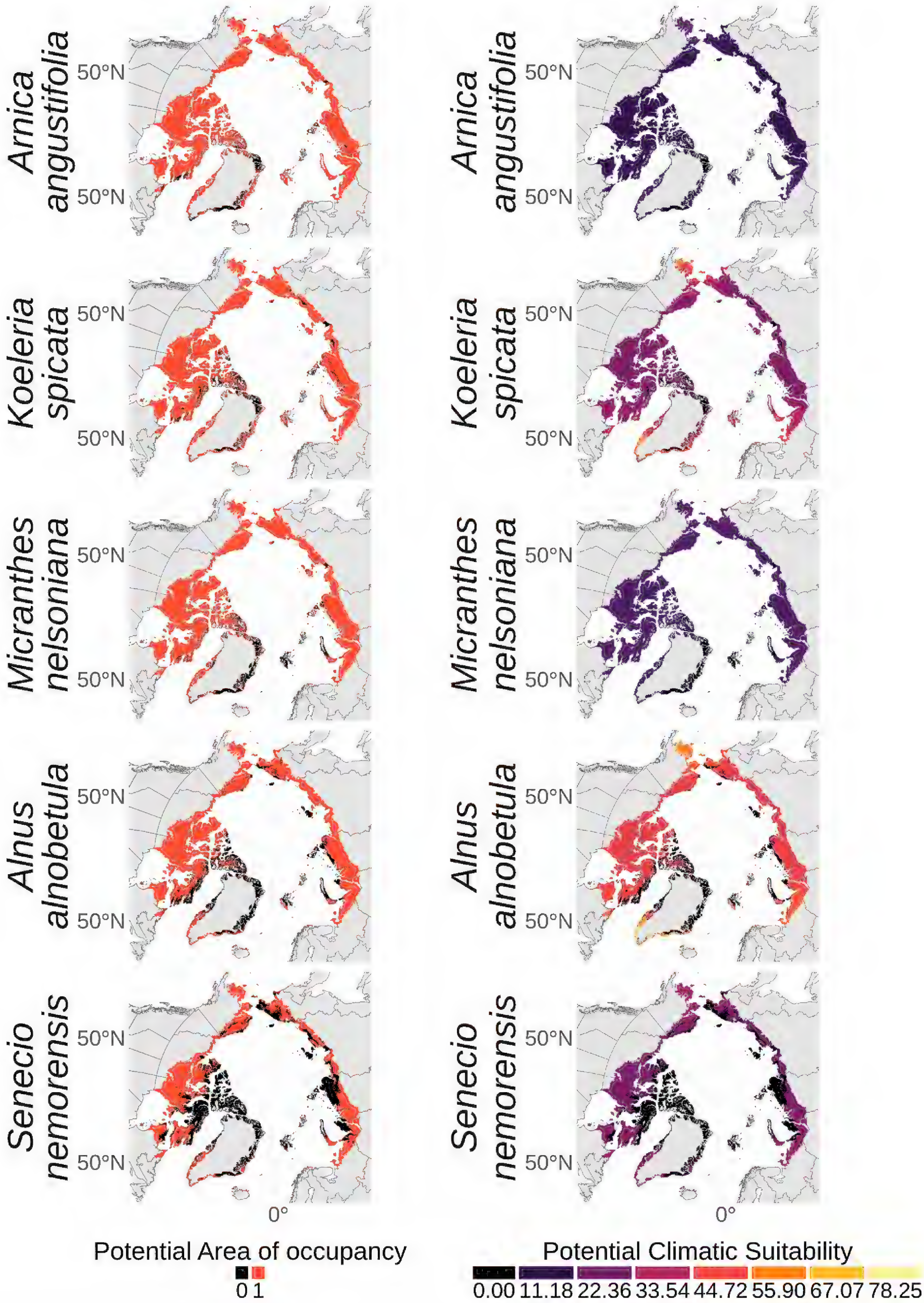

Figure 3. Potential distribution of the top five potential new alien vascular plant species in the Arctic. Left panel: potential area of occupancy (regardless of probability). Red areas indicate potential presence, while black areas indicate no potential occupancy. Right panel: potential climatic suitability. Warmer colors (yellow to red) indicate higher climatic suitability for the species.

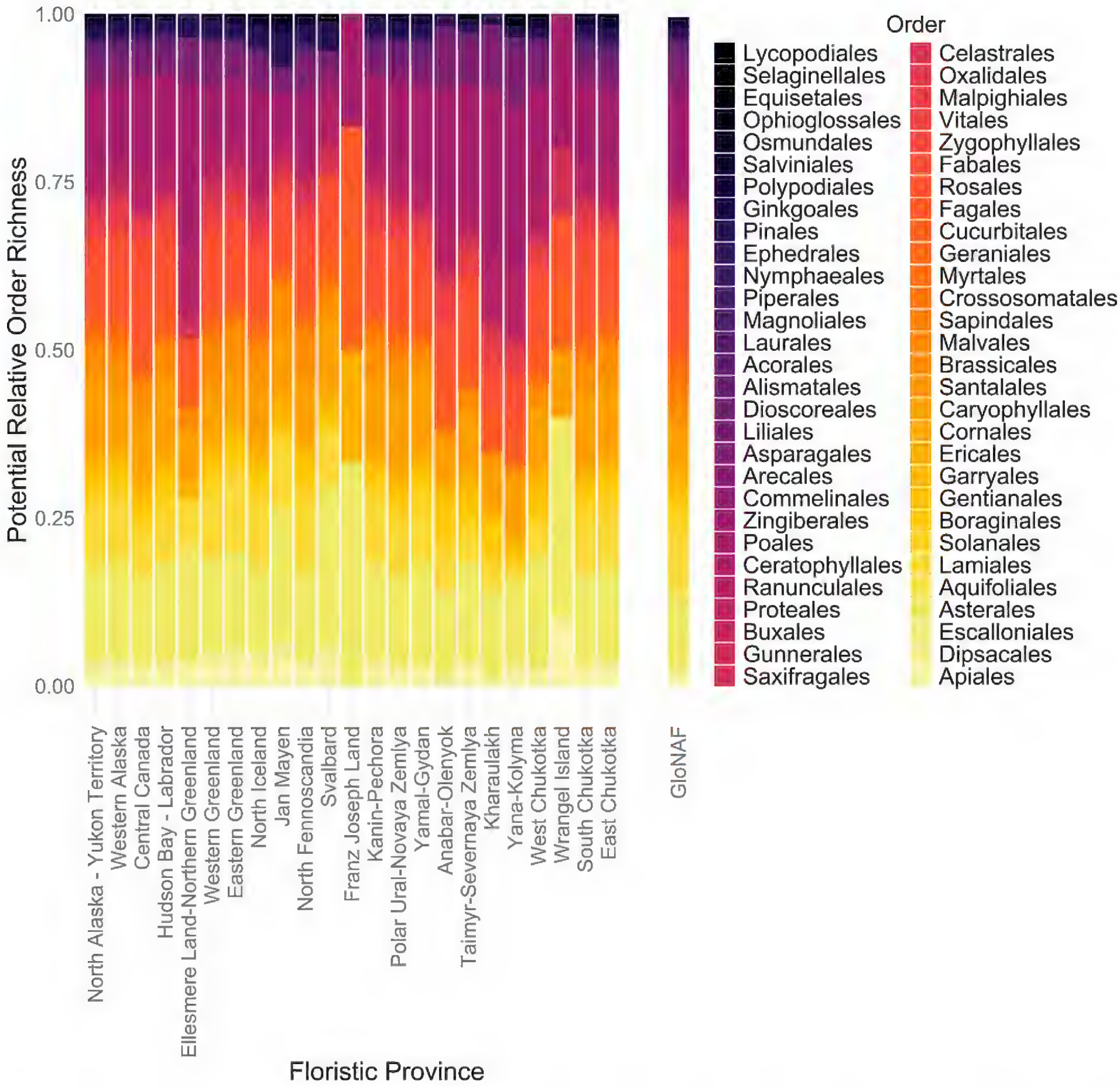

Figure 4. Taxonomic composition of potential new alien taxa across Arctic floristic provinces. The bars represent the relative richness of each taxonomic order within each floristic province, sorted from west (left) to east (right), and include the comparison with the GloNAF database as a separate bar on the right side. Different colors represent different taxonomic orders.

were entirely absent from Franz Joseph Land. Wrangel Island showed the next largest deviation (V = 0.32), suggesting a medium effect size, although this was not statistically significant after FDR correction ($p_A d_j$ = 0.069). This moderate effect was associated with an overrepresentation of Asterales (30.0% vs. 11.8% GloNAF) and Poales (20.0% vs. 13.0% GloNAF), along with the complete absence of Fabales. All remaining floristic provinces exhibited small effect sizes (V < 0.3) and were not statistically significant ($p_A d_j$ > 0.8). In the Kharaulakh province, compositional distinctiveness was mainly driven by a high relative richness of Poales (25.4% vs. 13.0% GloNAF). A consistent pattern across nearly all provinces was the marked underrepresentation of Fabales. Despite being a major alien plant order globally, Fabales was absent from all high-Arctic island provinces and accounted for less than

7.1% of potential alien richness in the remaining provinces—a pattern likely influenced by the order's naturally limited distribution in the Arctic.

The potential new alien species identified in this study originate from a wide range of botanical countries worldwide (Fig. 5; Suppl. material 1: table S5; Suppl. material 2: province_origin_connections.csv). Notable source countries in Europe include Germany with 1,787 species, France with 1,707 species, Sweden with 1,658 species, and Austria with 1,618 species. North America also contributes significantly, with notable sources including Ontario (1,072 species), Colorado (1,043), New York (1,030), and California (1,021). Other botanical countries such as Kazakhstan (609), China Southeast (344), and Argentina Northeast (395) were also identified as potential sources for a notable number of species. One species, *Hylotelephium maximum* (L.) Holub, was recorded as observed in the Antarctic according to GBIF, but we consider this an erroneous occurrence record.

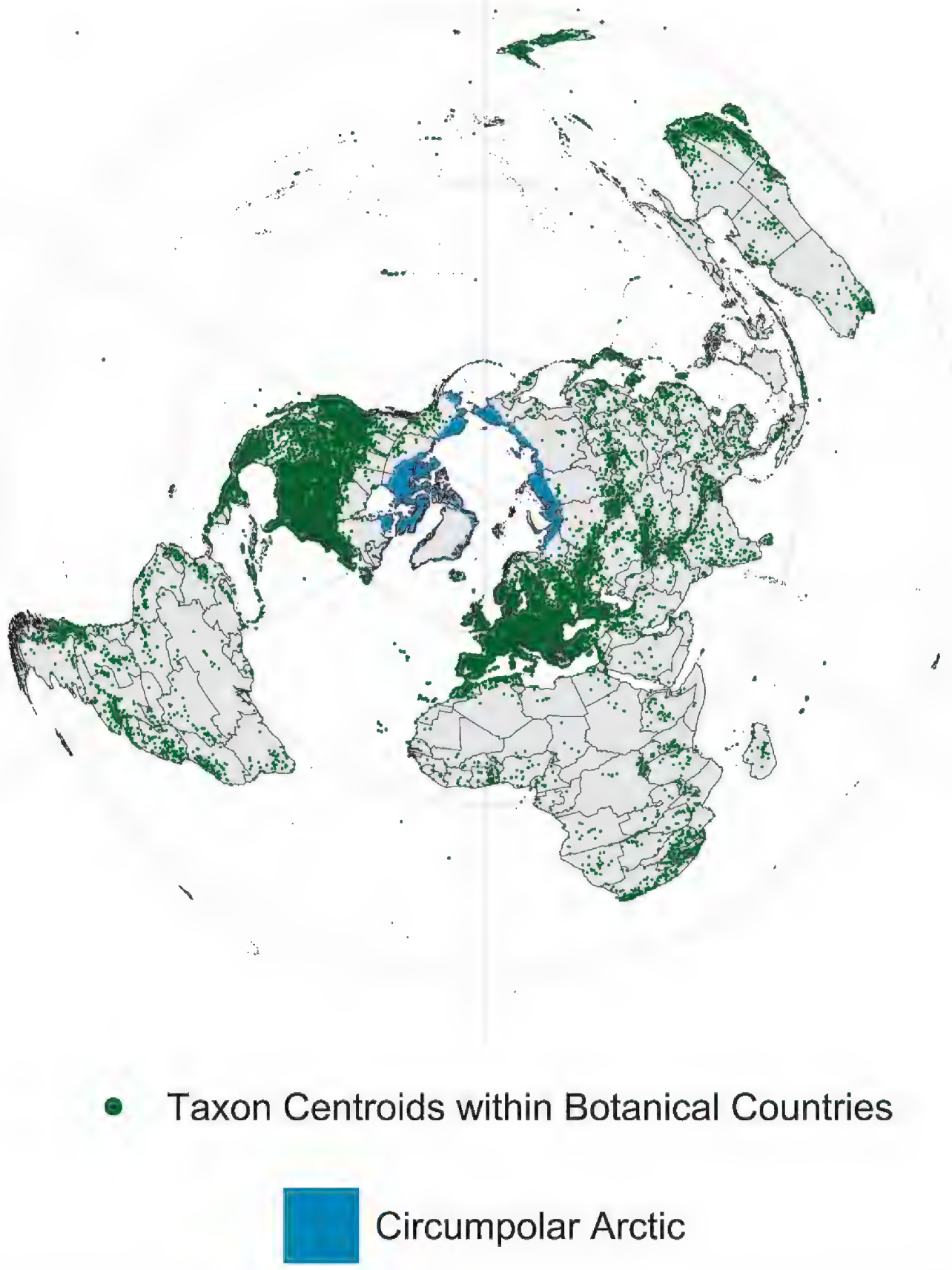

Figure 5. Potential source regions for new alien taxa to the Arctic. Green points indicate species centroids within botanical countries around the world (based on the World Geographical Scheme for Recording Plant Distributions), representing potential source regions. The blue area outlines the Arctic.

Both AIC and BIC consistently identified the full model as the best-fitting, providing strong support for the inclusion of latitude as a predictor of all three components: the mean climate overlap, its variance, and the probability of zero overlap (Suppl. material 1: table S1). In this optimal model, climate overlap increased significantly with absolute latitude ($\beta = 0.015$, SE = 0.003, $p < 0.001$), indicating that taxa with distributions centered at higher latitudes were more likely to find suitable climatic conditions in the Arctic (Fig. 6). Simultaneously, the probability of zero overlap decreased with latitude ($\beta = -0.230$, SE = 0.005, $p < 0.001$), as did the variance in overlap values ($\beta = -0.014$, SE = 0.003, $p < 0.001$), suggesting a more consistent and widespread climatic suitability among high-latitude taxa.

Discussion

Our study identifies 2,554 potential new alien vascular plants that have a climatic niche overlap in the Arctic. We reveal clear spatial patterns in climate suitability across Arctic floristic provinces and locate potential hotspots in southern regions, including western Alaska and northern Fennoscandia. The majority of species displayed limited predicted occupancy, with only 42 species exceeding 20% potential coverage of the terrestrial Arctic region. The highest predicted occupancies were found among four species that—following the precautionary principle and taxonomic filtering criteria—already have recorded occurrence points for one or several infraspecific taxa within the

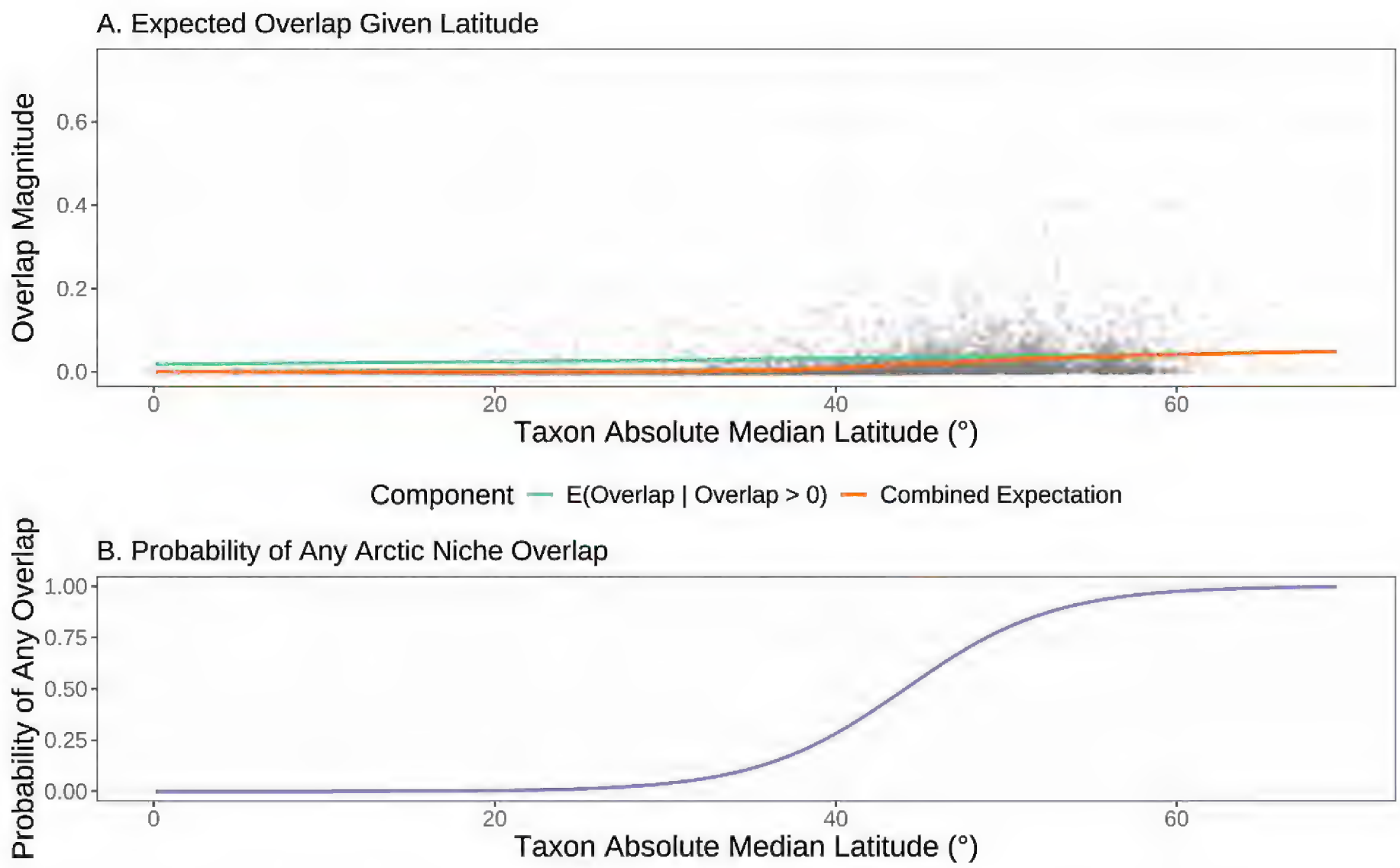

Figure 6. The relationship between taxon's absolute median latitude and Arctic niche overlap presented in two panels. Panel **A** (top) shows the expected overlap magnitude given latitude. Gray points represent individual species data, while the green line represents the conditional expected overlap when overlap exceeds zero (E(Overlap | Overlap > 0)), and the orange line shows the combined expectation. Panel **B** (bottom) displays the probability of any Arctic niche overlap as a function of latitude, shown by the blue curve. Together, these panels demonstrate that both the probability of Arctic niche overlap and its expected magnitude increase with species' absolute median latitude, with the probability approaching 100% at the highest latitudes (> 60°).

Arctic. Additionally, species currently established in adjacent biogeographic zones, such as *Senecio nemorensis* L. (62% occupancy) and *Thalictrum foetidum* L. (51%), showed high potential climate suitability in the Arctic (Derived dataset GBIF.org 2025b). This finding is consistent with earlier studies showing that proximity to the Arctic enhances the likelihood of successful establishment (Cazzolla Gatti et al. 2019; Wasowicz et al. 2020; Hansson et al. 2023). Climatic overlap increased significantly with the median latitude of species' current ranges, supporting our hypothesis that taxa from higher latitudes are more likely to encounter suitable climates in the Arctic.

Compiling a list of relevant taxa for horizon scanning involves gathering species occurrence data and their alien status and harmonizing inconsistencies in taxonomy and nomenclature from different data providers and sources varying in accuracy and age. Our data-driven workflow effectively collates and mass-curates digital taxon data from site-specific taxon lists and databases, employs a taxonomic backbone to harmonize nomenclature across data providers, and flags cases for manual review. Through the climate suitability analysis, we then generate a prioritized list of relevant potential new alien taxa to the Arctic based on macroclimatic niche overlap, providing a foundation for further assessment of their introduction pathways, invasion risk, and ecological impacts.

Of the top five potential new alien species in the Arctic (Fig. 3), only *Senecio nemorensis* L. (Asteraceae), with its five recognized subspecies, does not currently have any occurrence points within the Arctic. *S. nemorensis* is native to central Europe and Asia and is listed as a naturalized alien species in Norway, Sweden, Latvia, the United Kingdom, and Belgium (van Kleunen et al. 2019). In mainland Norway, *S. nemorensis* is recognized as an alien "doorknocker" species—defined as not yet able to reproduce in Norwegian nature but expected to do so within 50 years (Sandvik et al. 2020)—with a large invasion potential and assessed as potentially high risk in terms of ecological impact (Alm et al. 2023). The remaining four top potential new alien species to the Arctic all belong to species complexes, each with several infraspecific taxa, of which one or more occur in the Arctic. Our workflow initially excluded all taxa already present in the Arctic; however, following the precautionary principle, and because GloNAF mainly includes information at the species level, all infraspecific taxa were reintroduced into the workflow at the occurrence data stage (stage 4; Fig. 1) if a species was listed as "naturalized" or "alien" by GloNAF and not excluded by the Arctic Plant Inventory List or the Arctic Alien Plant List. These taxa may include other infraspecific taxa naturalized outside the Arctic that could represent potential new aliens to the Arctic. Our data-driven workflow therefore requires taxonomic expert-based curation at key stages to determine whether flagged cases should be corrected and returned to the workflow (e.g., stage 2; Fig. 1), as well as during the interpretation of taxon lists after horizon scanning.

As Whitley et al. (2025) emphasize, systematic taxonomic harmonization is not an optional data-cleaning step but a fundamental prerequisite for reliable digital biodiversity analysis. Our workflow was designed specifically to address this prerequisite by tackling inherent challenges such as nomenclatural instability, synonym proliferation, and inconsistent taxonomic concepts. By employing a standardized taxonomic backbone (WFO) for automated harmonization while strategically flagging complex cases for expert review, our approach balances computational efficiency with taxonomic rigor. For instance, our process flagged "672109 *D. pseudo-oxycarpa*" (Arctic Plant Inventory List; Daniëls et al. 2013), which was passed as *Draba pseudo-oxycarpa* to WFO.match and initially returned as *Draba* L.

Manual review revealed it as a contested name in the Pan-Arctic Flora related to *Draba oxycarpa* Sommerf., allowing us to correct it before returning it to the workflow. Despite the sophisticated harmonization process, some limitations remain. We identified 26 autonyms that passed through the pipeline, and some verbatim names required assumptions about authorship (e.g., assuming "L." for "470503 S. villosum (ssp. villosum)," i.e., *Sedum villosum* L., from the Arctic Plant Inventory List; Daniëls et al. 2013). Furthermore, our reliance on the WFO.one function for duplicate synonym resolution without manual checks could potentially lead to some misapplied names. These persistent challenges highlight the complexity of maintaining the stable taxonomic foundation that Whitley et al. (2025) call for.

Several species with known Arctic distributions belong to taxonomic complexes with multiple subspecies, some or all of which are known to be naturalized elsewhere in the world according to GloNAF (van Kleunen et al. 2019). For example, the species with the highest predicted occupancy in the Arctic is the grass *Koeleria spicata* (L.) Barberá, Quintanar, Soreng & P.M. Peterson (Fig. 3). Given its extremely wide range—including the entire Arctic and all major temperate mountain regions extending into the tropics and the Southern Hemisphere—its top ranking in our horizon scanning is neither surprising nor an error. Rather, it serves as a useful example of how an expert committee tasked with compiling a list of relevant species for ecological impact assessments might apply and interpret our workflow and results. *Koeleria spicata* comprises three recognized subspecies, one of which (subsp. *spicata*) is widespread in the Arctic. This subspecies, with all its Arctic occurrences, was therefore first excluded from our workflow. However, the species is listed as a naturalized alien on the sub-Antarctic islands of Kerguelen by GloNAF (under the synonym *Trisetum spicatum*) and was therefore re-included at the species level at a later step in the workflow. For similar reasons, the following taxa also show high potential occupancy in the Arctic: the circumpolar *Arnica angustifolia* Vahl complex (three subspecies, all present in the Arctic, with naturalized populations in Ontario, Canada, and Argentina); the nearly circumpolar *Alnus alnobetula* (Ehrh.) K. Koch (five subspecies, including the Arctic subsp. *crispa*, naturalized in Norway, Iceland, Spain, Slovakia, New Zealand, and the United States; Hegre et al. 2023); and the species complex *Micranthes nelsoniana* (D. Don) Small (five to six varieties, most present in the Arctic, subsp. *nelsoniana* [syn. *Saxifraga arguta*] naturalized in Mexico).

The potential source regions for new alien plant species in the Arctic extend globally across nearly all climate zones (Fig. 5). This global extent of source regions—with substantial contributions from temperate regions in Europe (e.g., Germany and France) and North America (e.g., Ontario and Colorado), as well as from distant areas such as Kazakhstan and Argentina—highlights how diverse introduction pathways created by global trade and transportation networks can facilitate introductions from multiple regions. This demonstrates that a species' climate match between a specific source region and the Arctic does not need to be high for that species to have strong establishment potential, owing to its broader climatic niche breadth across its known range, including climates more analogous to the Arctic. In addition, the observed patterns in taxonomic composition across Arctic floristic provinces appear to align with our climate suitability findings. Floristic provinces showing the highest deviations in order composition—particularly the island provinces such as Franz Joseph Land and Wrangel Island—also exhibited distinct patterns in climate suitability for potential new alien species. This result indicates that the higher latitudes of the Arctic may be less vulnerable to introductions than lower latitudes.

Such widespread source geography and composition present significant challenges to biosecurity efforts, as they imply that preventive measures cannot focus exclusively on particular geographic pathways. As identified by Wasowicz et al. (2020), "escape from confinement," "transport–stowaway," "seed contaminant," and "transport via vehicles" represent the historically most active introduction routes, while many introductions remain classified with an unknown pathway. These diverse pathways, combined with our findings of the global extent of potential source regions, underscore the need for comprehensive monitoring and prevention strategies at key entry points. Localized areas of high climatic suitability for multiple species—particularly in southeastern Greenland and western Alaska—suggest potential invasion hotspots warranting targeted biosecurity measures within these regions (Pfadenhauer et al. 2024). Focusing biosecurity efforts on common points of entry such as ports, airports, research stations, urban regions, and tourism hubs that connect to the identified hotspot regions (for example, those in western Alaska, southwestern and southeastern Greenland, northern Iceland, northern Fennoscandia, and Kanin–Pechora) provides a practical and efficient approach to intercepting potential new alien taxa before introduction.

The diversity of source regions suggests a complex interplay between plant traits and human-mediated factors in determining Arctic introduction potential. While physiological traits related to cold stress adaptations, competitive ability, dispersal limitations, and microclimate requirements may currently limit establishment (Huner et al. 1993; Buchanan et al. 2015; Keddy 2017; Nievola et al. 2017; Zhou et al. 2023; Speed et al. 2024), increasing human activity and warming temperatures are likely to enhance establishment potential (Ware et al. 2012; Wasowicz et al. 2020; Sandvik et al. 2022; IPBES 2024; Pfadenhauer et al. 2024). Human disturbance could bridge climate gaps by creating favorable conditions in disturbed and nutrient-enriched soils (Alsos et al. 2015; Doetterl et al. 2022; Da Silva and Kotanen 2024; Speed et al. 2024). This human-mediated "climate bridging" means that even taxa from climatically dissimilar regions may successfully establish if introduced with sufficient frequency to distributed areas, emphasizing that both trait-based approaches and analyses of human activity patterns are essential components of comprehensive risk assessments in the rapidly changing Arctic landscape. Future research should focus on points of entry in regions with high climatic suitability or on pathway subcategories with the greatest volume of introductions, such as soil import and human travel (Ware et al. 2012; CBD 2014; Sandvik et al. 2022; IPBES 2024).

While our climatic niche horizon scanning approach allowed analysis of extensive datasets compared to expert consensus methods, we acknowledge several considerations that inform future research directions. Taxonomic standardization challenges included the necessary collapsing of certain infraspecific taxa into species-level classifications, which contributed to some apparently novel potential new alien candidates already having conspecific populations in the Arctic. Occasional misclassifications or errors in data labeling are possible (e.g., *Hylotelephium maximum* (L.) Holub had an erroneous record in the Antarctic and was initially included in our dataset). The exclusion of taxa with fewer than 55 occurrences represents a methodological choice that strengthens confidence in our findings while highlighting opportunities for refinement. Geographic and temporal biases in GBIF data (Meyer et al. 2015; Troudet et al. 2017; Bowler et al. 2022) were partially mitigated through our climatic niche overlap approach by cleaning and thinning occurrences rather than relying on raw occurrence data.

To build upon this foundation, future work could (1) incorporate future climate scenarios to evaluate changing invasion risks under varying warming conditions; (2) integrate additional environmental variables and taxon traits, such as Ellenberg Indicator Values and competitor–stress-tolerator–ruderal (CSR) strategies, to improve establishment predictions; and (3) implement weighted resampling approaches to further address sampling bias (Meyer et al. 2015; Chen et al. 2024). These enhancements would address the inherent constraints of our current methodology while maintaining its scalability and adaptability as data quality improves, ultimately providing a framework for ongoing risk assessment that can evolve with changing Arctic conditions. We also note that ongoing collection and digitization efforts will increase data availability and, hence, the applicability of our approach in many parts of the world and may also reduce existing biases in the data.

Conclusion

The Arctic region faces an escalating threat from biological invasions driven by increased human activity and climate change. This study employed a data-driven climatic niche horizon scanning approach to identify 2,554 potential new alien vascular plant taxa with climatic niche overlaps in the Arctic under current climate conditions. Six major hotspots were detected, highlighting the pressing need for enhanced biosecurity measures in provinces such as western Alaska, southwestern and southeastern Greenland, northern Iceland, northern Fennoscandia, and Kanin–Pechora. While many potential new alien taxa exhibited low climatic overlap, their establishment could be facilitated by increasing human disturbance, such as in disturbed, nutrient-enriched soils, as well as by climate change impacts. Taxa with high-latitude distributions demonstrated greater potential for occupancy in the Arctic. In a rapidly warming Arctic, some introduced taxa may provide ecological functions or services that support ecosystem resilience, while others may disrupt existing ecological relationships. Management approaches must therefore balance monitoring of potentially harmful invasions with recognition of the inevitability of ecological change in the region. Collaborative efforts among citizens, researchers, policymakers, and stakeholders are essential to develop adaptive management strategies that acknowledge both the risks and potential benefits of newly arriving taxa in the transforming Arctic landscape.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

Grammarly, Microsoft Copilot, and Claude (Anthropic) were used for spell-checking, grammar correction, and suggestions on synonyms to improve readability. During programming, Microsoft Copilot was used to look up functions and packages, while Claude (Anthropic) was used to improve function design and code structure.

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Author contributions

Tor Henrik Ulsted: Conceptualization (supporting); Data curation (lead); Formal analysis (lead); Methodology (equal); Software (lead); Validation (equal); Visualization (lead); Writing – original draft (lead); Writing – review and editing (equal). Kristine Bakke Westergaard: Conceptualization (supporting); Data curation (supporting); Methodology (equal); Funding acquisition (equal); Supervision (equal); Validation (equal); Writing – review and editing (lead). Wayne Dawson: Validation (equal); Writing – review and editing (equal). James D. M. Speed: Conceptualization (lead); Formal analysis (supporting); Methodology (equal); Funding acquisition (equal); Supervision (equal); Validation (equal); Writing – review and editing (equal).

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Data availability

The dataset and source code used in this study are available as follows:

1. A full description of the bioinformatics pipeline alongside the source code is available on GitHub (https://doi.org/10.5281/zenodo.15802292).
2. Raw output files from the climate niche space analysis. The data encompass the complete analytical workflow from initial data wrangling through final post-analysis outputs, providing full transparency and reproducibility for the research (https://doi.org/10.6084/m9.figshare.29402192.v1).
3. The derived dataset for potential new alien taxa includes GBIF occurrence data for taxa with potential for climatic overlap with the Arctic (https://doi.org/10.15468/DD.2KMYM8).
4. The derived validation dataset includes GBIF occurrence data for taxa currently found in the Arctic, serving as the validation dataset for this project (https://doi.org/10.15468/DD.Z5B8X5).

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Supplementary material 1

Horizon scanning of potential new alien vascular plant species and their climatic niche space across the Arctic

Authors: Tor Henrik Ulsted, Kristine Bakke Westergaard, Wayne Dawson, James D. M. Speed

Data type: pdf

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Supplementary material 2

CSV datasets

Authors: Tor Henrik Ulsted, Kristine Bakke Westergaard, Wayne Dawson, James D. M. Speed

Data type: zip

Explanation note: Zip file with archive containing three CSV datasets with climate niche analysis results and origin–destination connections for vascular plant species in Arctic floristic provinces: (1) included_species.csv—climate analysis results for species included in hypervolume analysis; (2) excluded_species.csv—data for species excluded from final analysis; (3) province_origin_connections.csv—unique taxa counts by origin country and floristic province. See the README file inside the archive for detailed column descriptions and examples.

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